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Project X Broader Impacts Spallation & Irradiation Facility

DM ASNER, MA PETERSON, D SENOR, DW WOOTAN

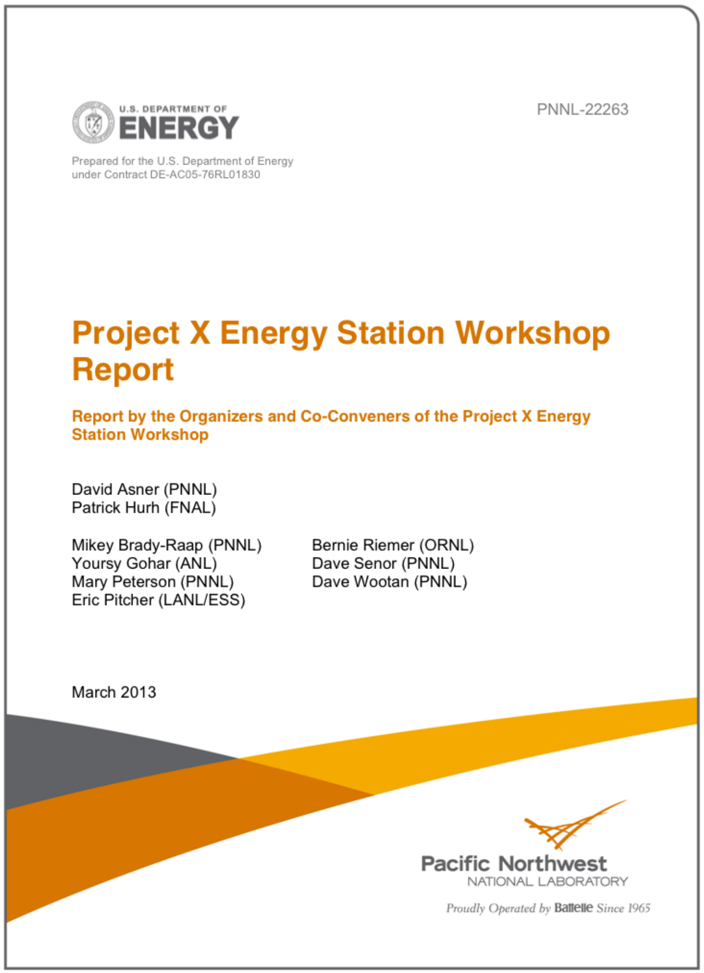
Community Summer Study 2013 (Snowmass on the Mississippi)

30 July 2013

Introduction/Summary

- Project X Spallation and Irradiation Facility described
  - Volume 3: Project X Broader Impacts arXiv:1306.5024 **[physics.acc-ph]**
- Content of this volume draws heavily on previous workshops & reports
  - Project X Energy Station (PXES) Workshop, January 29-30, 2013
  - PX Forum on Spallation Sources for Particle Physics, March 19-20, 2012
- The PXES Workshop included participants from the Nuclear Energy and the Fusion Energy community and participants for DOE-NE HQ
- *The Project X Energy Station as a Candidate Fusion Materials Facility* was submitted to FESAC as part of the SC future facilities exercise
  - Fusion Nuclear Materials Facility deemed "Absolutely Central"
- Briefed both SC-FES and DOE-NE on PX Materials Irradiation Facility
- (Substantial) effort required to evolve the Integrated Target Station (Energy Station + Nuclear Physics) to a pre-Conceptual Design
  - Need to engage DOE-NE, DOE-SC-FES and their research communities

Project X Energy Station Workshop
January 29-30, 2013



U.S. DEPARTMENT OF ENERGY

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Project X Energy Station Workshop Report

Report by the Organizers and Co-Conveners of the Project X Energy Station Workshop

David Asner (PNNL)
Patrick Hurh (FNAL)

Mikey Brady-Raap (PNNL)
Yoursy Gohar (ANL)
Mary Peterson (PNNL)
Eric Pitcher (LANL/ESS)
Bernie Riemer (ORNL)
Dave Senor (PNNL)
Dave Wootan (PNNL)

March 2013

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Workshop objectives

- Identify & explore the nuclear and fusion energy relevant R&D that would be possible in an Energy Station associated with the Project X Linac
- Discuss the hypothesis that an Energy Station associated with Project X could accelerate and enhance the ability to test and evaluate early research concepts.
- Identify the synergy and benefit that the Project X Linac could bring to the nuclear & fusion energy communities.

Energy Station -> Integrated Target Station

Goal

- Develop integrated spallation target station concept to serve DOE-SC-HEP/NP/FES, DOE-NE experimental needs

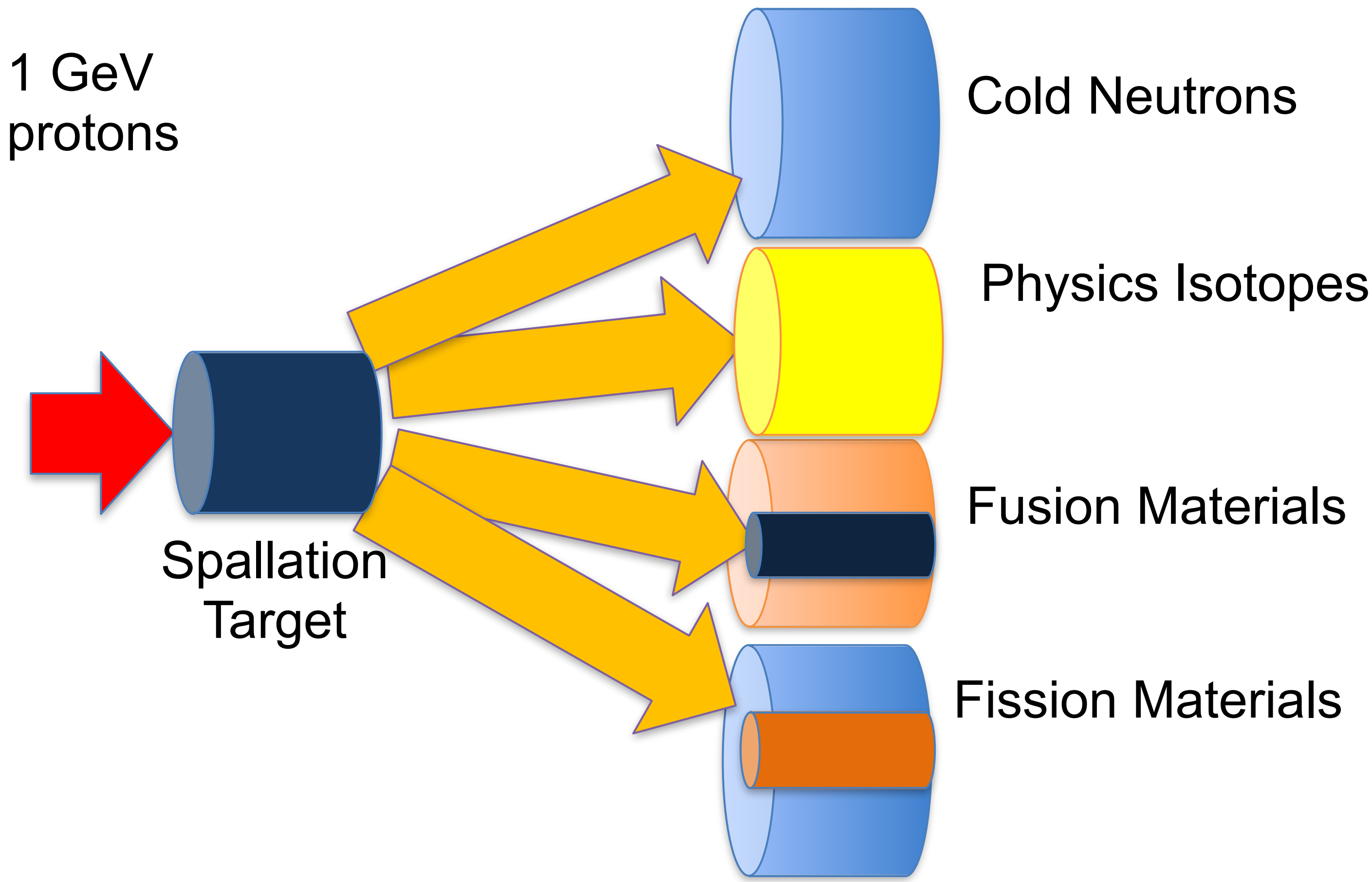
Rationale

- CW spallation neutron source could augment limited US irradiation testing capability
- Synergy between Physics experimental needs and materials testing for fusion, fission communities

Project X – Stage 1

- Could provide ~1 MW of beam dedicated to a spallation neutron source for nuclear materials and fuels research (Energy Station) or shared with a physics mission facility with similar neutron source requirements (Integrated Target Station)

Energy Station -> Integrated Target Station



Project X Integrated Target Station has the potential to benefit several areas (beyond HEP)

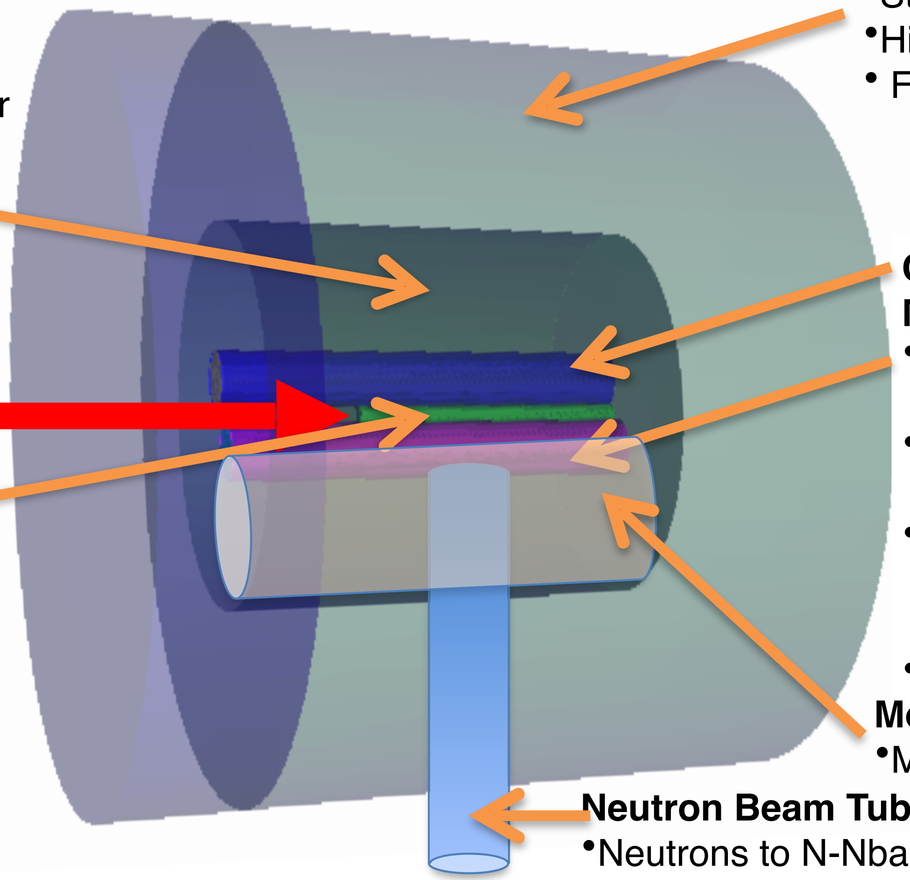
- Highest priority opportunities within the US Nuclear and Fusion energy programs are irradiation of fusion and fast reactor structural materials.
- Must provide a fusion and fast reactor relevant neutron flux at a minimum of 20 dpa per calendar year in a reasonable irradiation volume.
- Enable the in-situ real-time measurements of various separate-effects phenomena in fuels or materials, which would be very valuable to the modeling and simulation technical community. Such capabilities are more feasible in an accelerator-based system than a reactor
- Integral effects testing of fast reactor fuels, including driver fuel, minor actinide burning fuel, and transmutation of spent fuel.
- Support DOE Office of Nuclear Energy plus Office of Science programs
  - Materials Program - Fusion Energy Sciences (FES)
  - Isotope Production Program – Nuclear Physics (NP)
  - Ultra Cold Neutrons – Nuclear Physics (NP)

Integrated Target Station Concept

Lead Matrix Test Region
- Solid lead with gas or water cooling
- ~ 2 m diameter, 3 m length
- Low n absorb/ High n scatter
- High n flux/ Fast n spectrum
- Acts as gamma shield

Project X Proton Beam
- 1mA @ 1 GeV (1 MW)

Spallation Target
- Liquid Pb-Bi or Tungsten
- >30 neutrons/proton
- Protons penetrate ~50 cm
- Neutrons ~ fission spectrum
- ~ 10 cm dia, 60 cm length
- Cleanup system for spallation products



Reflector
- Steel/iron/nickel
- High n scatter
- Flattens n flux distribution

Closed Loop Test Modules
- Removable/replaceable/ customizable
- Independent cooling system
- n spectrum/material/ temp/pressure to match conditions
- ~30 cm dia

Moderator tank (if needed)
- Moderates neutrons for CN

Neutron Beam Tube
- Neutrons to N-Nbar, N-EDM experiments

Target Station Components – Spallation Target

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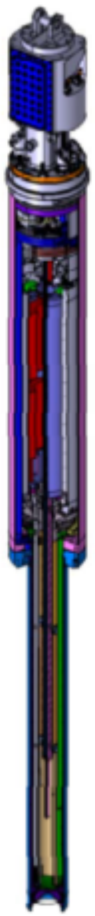
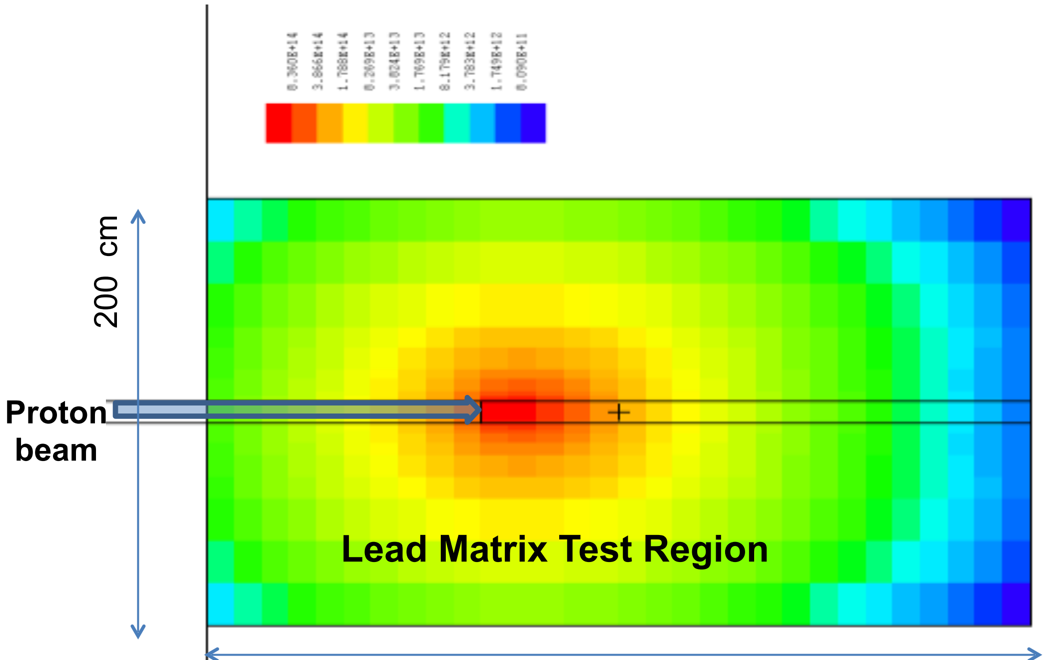
- Spallation Target:
  - 6.24e15 p/s proton beam
  - Nominal 10 cm diameter
  - High neutron yield Pb or LBE ~30 neutrons/proton
  - 1 GeV protons penetrate ~50 cm
  - Neutron spectrum similar to fission but with high energy tail
  - Coolant is target material, no stress issues in target
  - Beam window may be life limiting
    - Experience base from ISIS, SINQ, MEGAPIE, SNS, is ~7-22 dpa/yr on front window for SS316, T91, Inconel
    - For 10 cm diameter ESS window, ~8 dpa/yr
  - Need careful oxidation control, on-line cleanup
  - Spallation products like fission products
  - >400 KW energy deposited
  - Potential for in-beam materials testing

MEGAPIE (0.8 MW) LBE target has been demonstrated

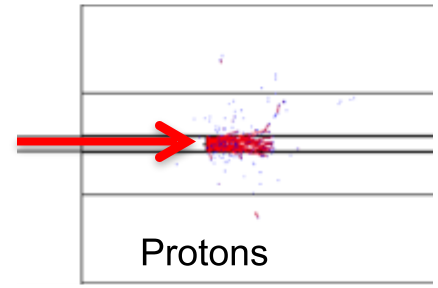


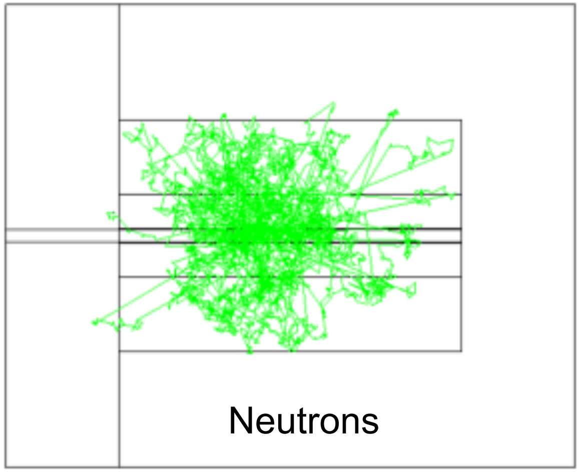
Target Station Components – Test Matrix

- Test Matrix
  - Solid lead or other (e.g. Zr-base alloy) – high scatter, low absorption
  - Maximizes neutron flux, provides space for array of test modules
  - Simple thermal analysis indicates heating may allow solid lead matrix
  - Beam tubes could provide additional testing flexibility



Neutron flux Distribution in Lead Matrix Test Region





High Flux Volumes Available in Test Matrix Region

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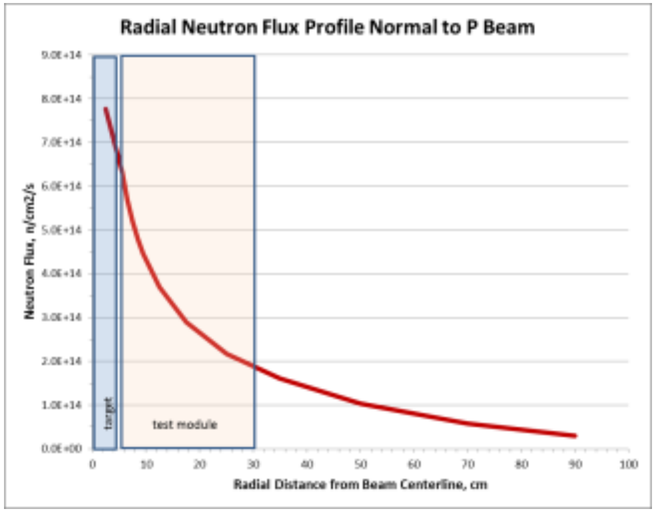
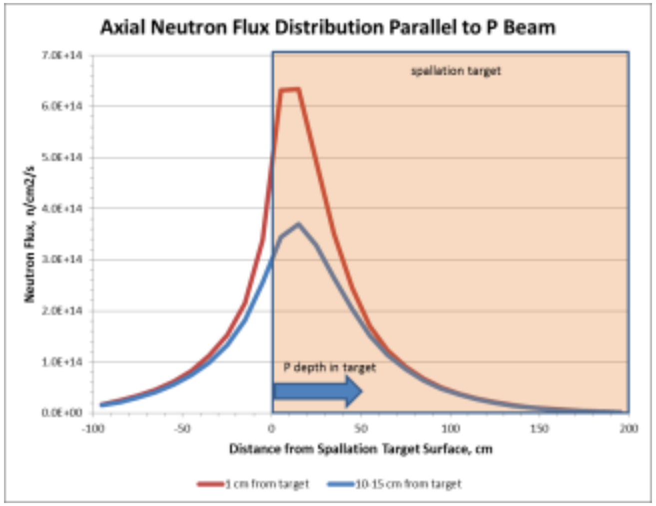
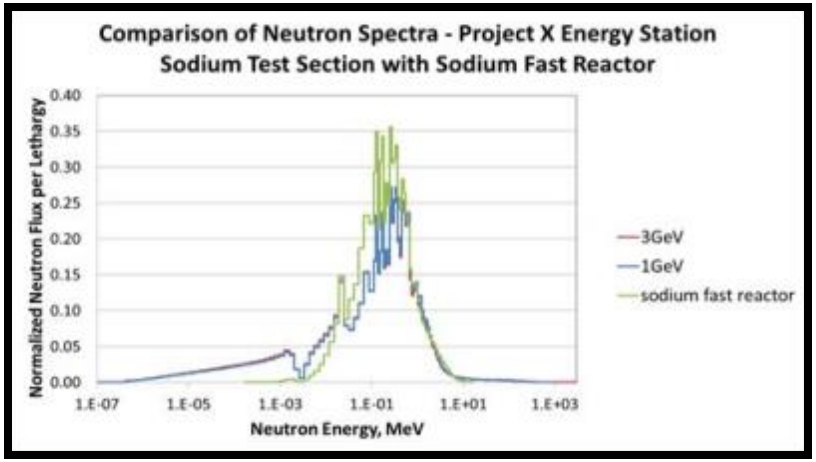
Neutron Flux Range (n/cm2/s)	Axial Extent (cm)	Outer Extent (cm)	Volume (liters)
>5e14	***30***	***8***	***~2.8***
>3e14	***50***	***15***	***~23***
>1e14	***110***	***60***	***~600***
>5e13	***160***	***80***	***~2000***
>1e13	***250***	***100***	***~9000***

- 1 GeV protons penetrate ~ 50 cm in lead or LBE target, generate ~30 neutrons/proton
- Neutron flux falls off radially but lead matrix helps
- Axial profile peaks ~20 cm below target surface, provides ~100 cm >1e14 $n/cm^2/s$

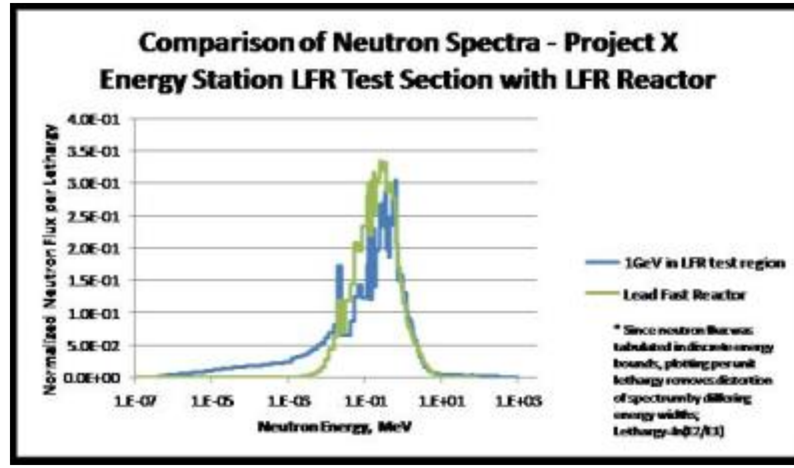




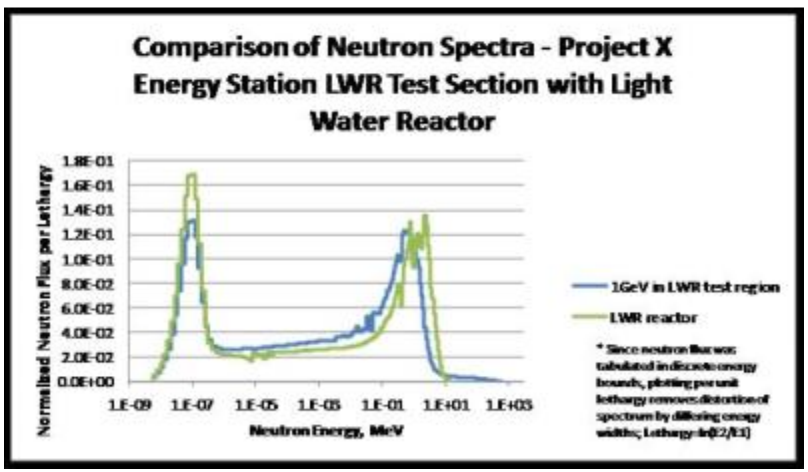
Spectrum Tailoring Can Simulate A Different Reactor in Each Module



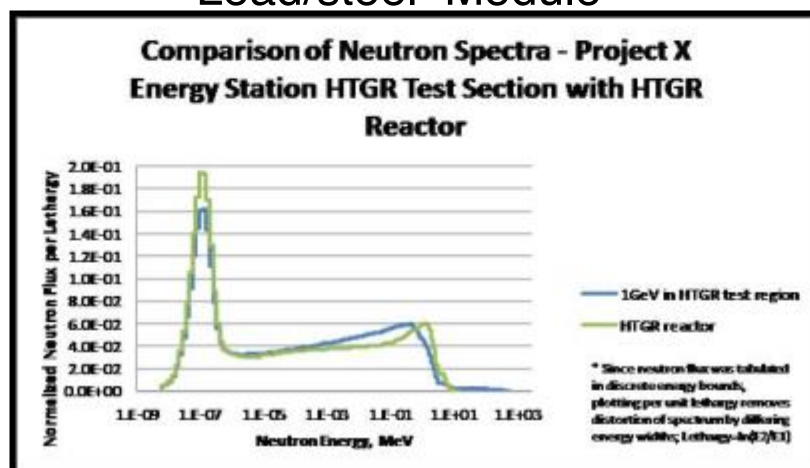
Sodium/steel Module



Lead/steel Module



Water/Zr Light Water Module



Graphite/He Module

How Does Target Station Compare?

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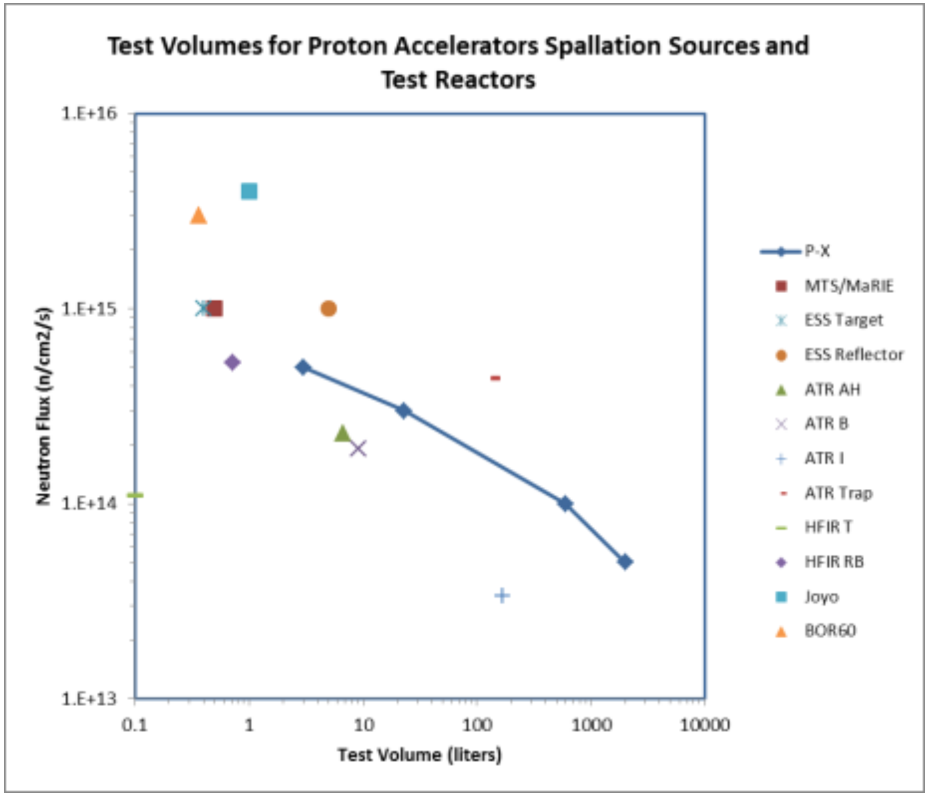
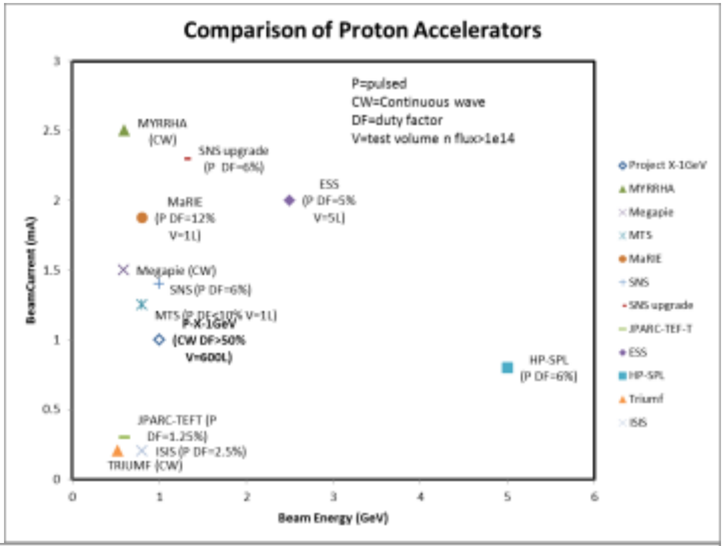
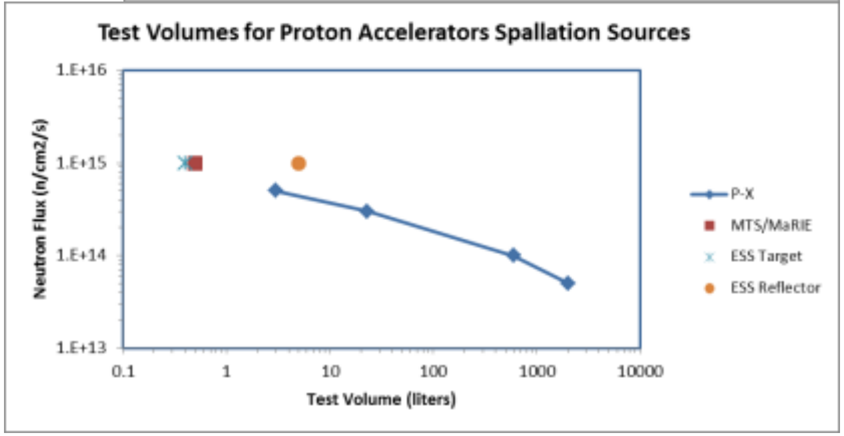






- Irradiation volumes at high flux comparable to reactors
- Accelerator parameters are in range of other proposed systems

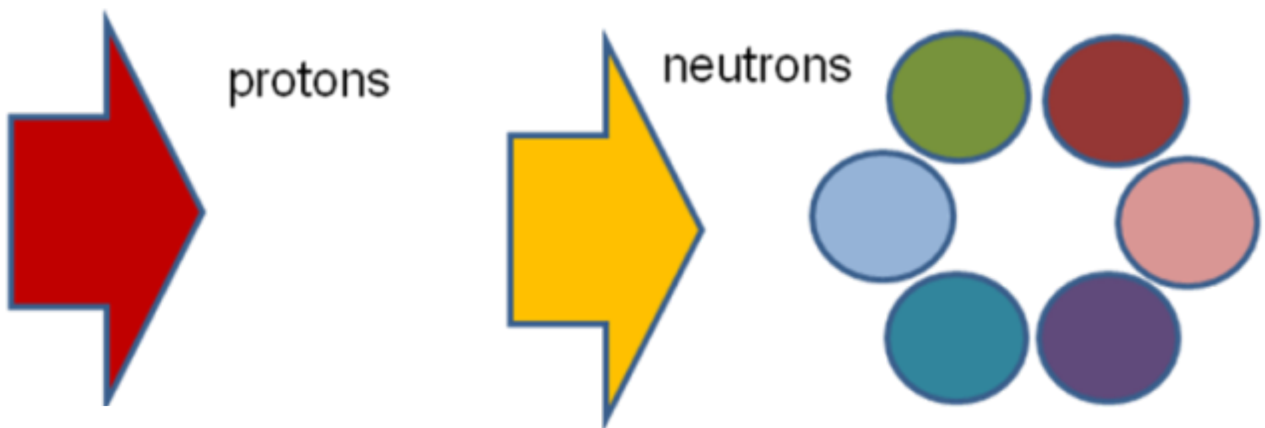
Actions identified to evolve concept

- Develop conceptual target designs that serve *both* particle physics and nuclear energy missions – Integrated Target Station (ITS)
- Develop an ITS testing program plan that capitalizes on the unique characteristics of a high-intensity accelerator and spallation source
- Define/refine the technical requirements to support the proposed testing program plan
- Compile relevant design parameters to support the high-priority mission needs and provide them to the beam and target designers
- Investigate the beam on/off issues for both short and long time scales. to determine which transients have the potential to be problematic due to thermal and radiation damage effects
- Further consideration must be given to desired damage rate/sample volume specifications to provide a meaningful irradiation capability
- Neutronics modeling of the notional Project X ITS concept needs to be refined to evaluate beam options (e.g., dual or rastered beam) to optimize flux and flux gradients in maximum usable test volumes.

Backup Slides

PNNL Target Station Concept

- A new approach utilizing the flexibility of an accelerator neutron source with spectral tailoring coupled with a careful design of a set of independent test loops can provide a flexible neutron test station for DOE applications

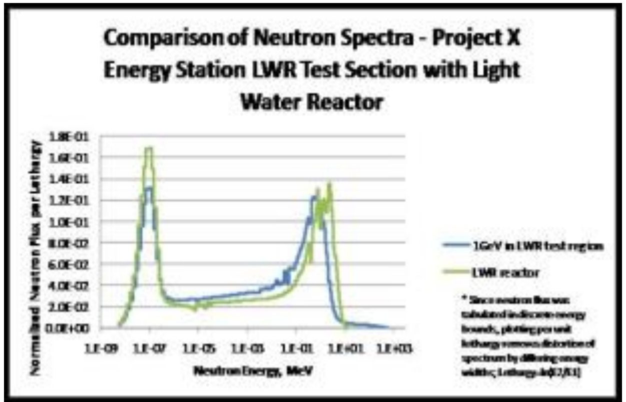


1MW CW Proton beam

Liquid metal spallation target

Closed Loop Modules for irradiation testing

Project X Energy Station Concept

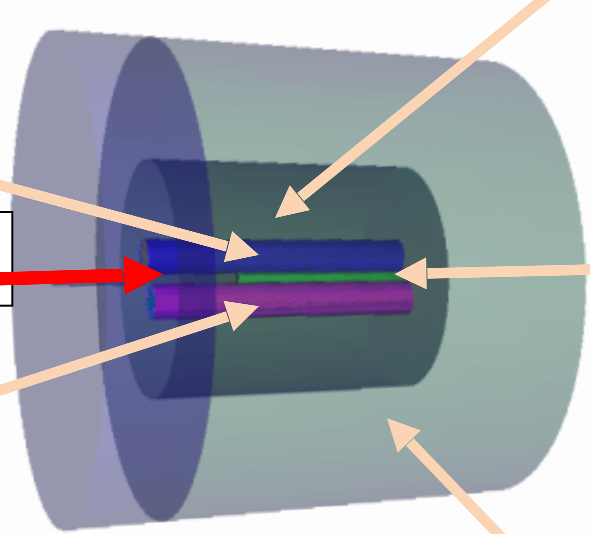


Thermal Spectrum Test Module: LWR, HTGR, MSR

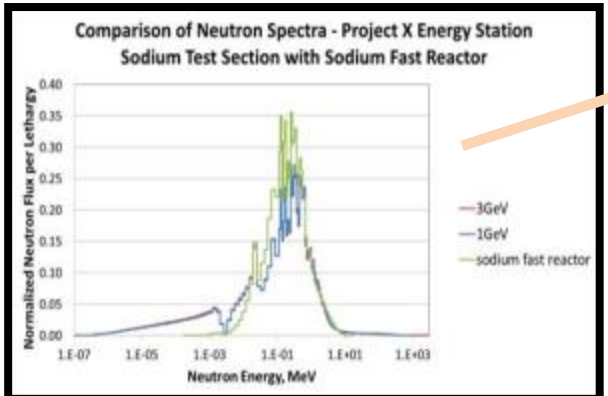
Closed Loop Test Modules
- Removable/replaceable/customizable
- Independent cooling system
- n spectrum/material/temp/pressure to match reactor conditions
- ~30 cm dia

Lead Matrix Test Region
- Solid lead with gas or water cooling
- ~ 2 m diameter, 3 m length
- Low n absorb/ High n scatter
- High n flux/ Fast n spectrum
- Acts as gamma shield

Project X Proton Beam
- 1mA @ 1 GeV (1 MW)



Spallation Target
- Liquid Pb-Bi
- >30 neutrons/proton
- 1 GeV protons penetrate ~50 cm in lead
- Neutrons Similar to fission spectrum
- Samples can be irradiated in proton beam
- Adding W or U can increase n flux density
- Small volume ~ 10 cm dia, 60 cm length
- Cleanup system for spallation products



Fast Spectrum Test Module: SFR, LFR, GFR

Reflector
- Steel/iron/nickel
- High n scatter
- Flattens n flux distribution

Target Station is Unique Combination of Existing Technologies

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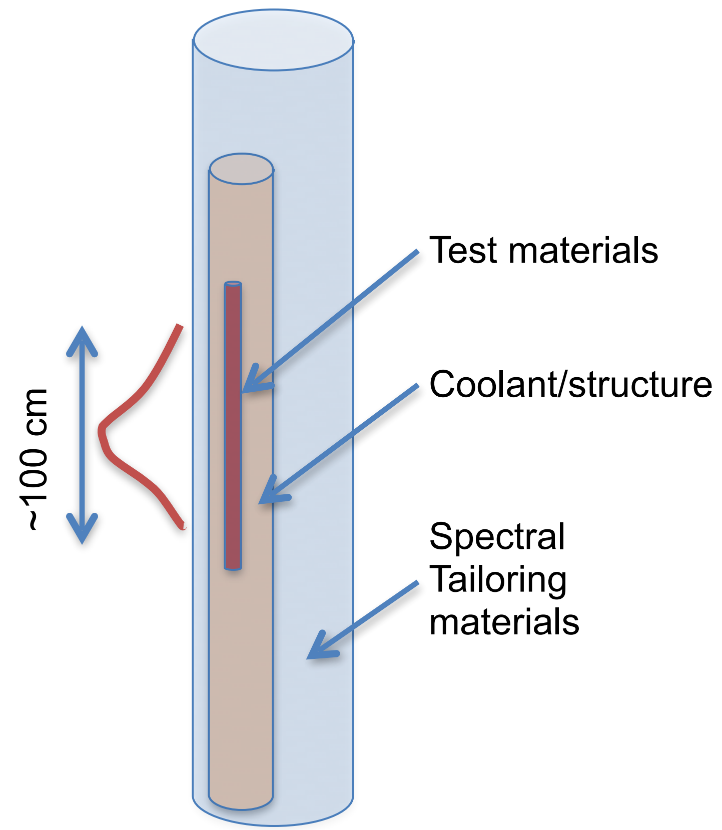
- Proton beam CW - 1 GeV - 1 mA - 1 MW
- Spallation Target:
  - Liquid lead or lead-bismuth release ~30 neutrons/proton
  - Neutron spectrum similar to fission spectrum but with high energy tail
  - Technology has been demonstrate at MEGAPIE
- Test Matrix
  - Solid lead or other (zircalloy) – high scatter, low absorption
  - Maximizes neutron flux, provides space for array of test modules
  - Simple solid block with cooling, holes for test modules
- Closed Loop Test Modules
  - Independently tailored irradiation environments (LWR, HTGR,SFR,LFR)
  - Independent heating/cooling system for each to control temperatures
  - Concept utilized in FFTF (sodium), BOR-60 (sodium, lead), ATR (press. Water)
- Reflector to minimize leakage neutrons

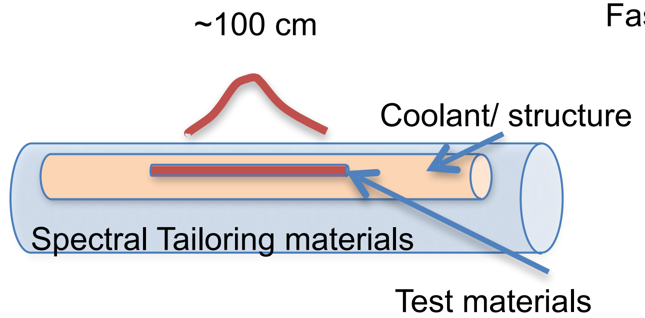
Target Station Components – Closed Loop Test Modules

- Number of modules can be varied
- Each module can have unique independent coolant and materials and operate at independent temperatures (sodium, lead, molten salt, water, helium)
- Neutron spectrum can be tailored from fast to thermal to match reactor conditions (the gamma to neutron ratio can also be tailored)
- Miniaturized test specimens can maximize testing in high flux region
- Modules are Removable, Replaceable, shipped offsite for post irradiation examination (PIE)

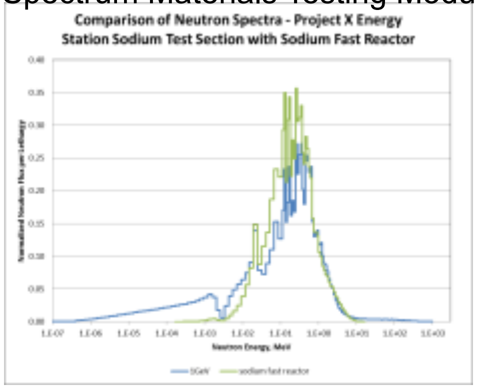


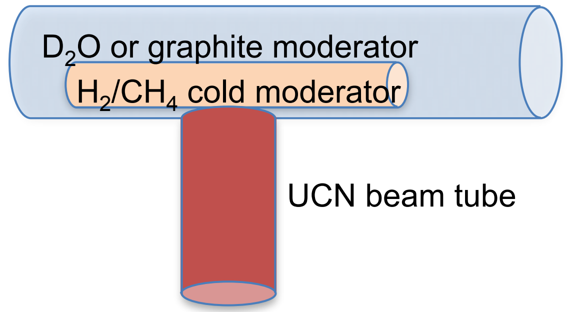
Closed Loop Modules

- Each module can have unique independent coolant and materials
- Removable/ replaceable/ customizable
- Independent cooling system
- n spectrum/ material/temp/ at desired conditions
- ~30 cm dia, 100 cm long test region

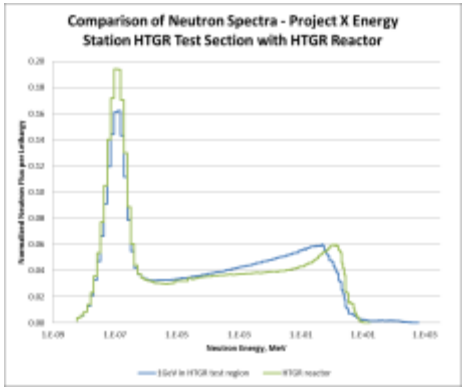


Fast Spectrum Materials Testing Module





Thermal Spectrum Module



DOE Office of Science – Fusion Energy Science

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R&D Scope	Environment	Testing Needs
Technology gaps requiring materials qualification • ***Plasma facing components*** • ***Low activation structural materials***	• ***14 MeV neutrons*** • ***Materials surrounding fusion ignition region*** • ***Tritium producing lithium blanket region***	• ***Structural material properties as a function of dpa and temperature*** • ***20-30 dpa/yr*** • ***Cumulative 150-200 dpa***

Target Station Can Help Fusion Energy Science Technologies

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- Dedicated fusion loop for materials testing with high energy neutron spectrum test environment at relevant temperatures
- Room for separate lead, helium, water loops that can be used to simultaneously test materials interactions
- The dpa accumulation and high energy neutron spectrum component can simulate fusion environments better than reactors
- Testing in the proton beam can provide high dpa and high neutron energies
- H and He generation rates for corresponding damage accumulation could allow testing of fusion materials
- Candidate fusion blanket materials can be irradiated in a prototypic coolant, temperature, and high neutron flux
- Temperature is a critical parameter in materials irradiation and precise temperature control will be a key aspect of the Energy Station Test Module design

DOE Office of Science - Nuclear Physics

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R&D Scope	Environment	Testing Needs
• *Source of Ultra cold neutrons for n-EDM, NNbar* • *Source of isotopes for ISOL atomic EDM*	• *Cold Neutrons* • *Very Cold Neutrons* • *Ultra Cold Neutrons* • *Well moderated neutron spectrum*	• *Stable, well characterized test environments* • *UCN n velocities <4mK* • *UCN density >3x10^4 UCN/cm^3* • *Beam tubes*

Target Station Can Help Nuclear Physics Technologies

- Separate closed loop with heavy water, Be, metal hydride, moderator region,
- Cryogenic cooled He, H2,HE-2, CH4 volume for producing Ultra cold neutrons,
- Reflected Cold Neutron beam transport to n-EDM, NNbar experiments
- Possibility for irradiating Thorium spallation target capsules in proton beam region to produce ISOL isotopes

DOE Office of Science – Isotope Production

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R&D Scope	Environment	Testing Needs
Radioisotope Production methodology	• ***Neutron spectrum tailored for specific isotopes*** • ***Easy access and retrievability***	• ***Low activation target and structural materials*** • ***Target/capsule compatibility***

Target Station Can Help Isotope Production Technologies

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- Dedicated isotope production loop with capability to vary neutron spectrum test environment and temperatures to optimize for isotopes of interest
- Room for separate loops that can be used to simultaneously produce and test a variety of isotopes
- Testing in the proton beam can provide accelerator produced isotopes
- Higher neutron energies than reactors can enhance production of isotopes only produced by fast neutrons
- Temperature is a critical parameter in some isotope target irradiations and precise temperature control will be a key aspect
- A rabbit system can be integrated into the test module for rapid insertion and retrieval of short lived radioisotopes
- Reflector region can utilize “waste” neutrons for beneficial isotope production such as ^{60}Co
- Spallation reactions produce broad range of reaction products and the target cleanup system could be designed to separate particular isotopes of interest

DOE Office of Nuclear Energy
Fuel Cycle R&D
Advanced Reactor Technologies

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R&D Scope

Advanced Reactor Technologies
- *Gen-IV, aSMR*
- *Basic physics*
- *Material research and testing*
- *Modeling and simulation of reactor systems and components*
- *Probabilistic risk analysis of innovative safety designs and features*
- *Development activities to establish concept feasibility for future deployment*

Fuel Cycle R&D
- *Material testing*
- *Structural materials*
- *Advanced nuclear fuels*
- *Reactor systems*
- *Instrumentation and controls*
- *Power conversion systems*
- *Process heat transport systems*
- *Dry heat rejection*
- *Separations processes*
- *Waste forms*
- *Modeling and simulation*
- *Small scale tests to validate system elements*

Environment

Sodium cooled fast reactor (SFR)
- *Sodium coolant Steel cladding*
- *Temperature range ~550 C*

Lead cooled fast reactor (LFR)
- *Fast spectrum*
- *Pb or LBE coolant Steel cladding*
- *Temperature range 500-800 C*

Gas cooled fast reactors (GFR)
- *Fast spectrum*
- *Temperature range ~600-850 C*
- *Helium coolant Steel cladding*

Very High Temperature Reactor (VHTR)
- *Thermal spectrum Graphite moderated*
- *TRISO fuel Helium cooled*
- *Temperature range ~1000 C*

Supercritical water cooled reactor (SCWR)
- *Thermal spectrum*
- *Light water coolant Steel cladding*
- *Temperature range ~550 C*

Molten Salt Reactor (MSR)
- *Thermal spectrum*
- *Sodium fluoride salt coolant*

Testing Needs

- *Structural material properties as a function of dpa and temperature*
- *Material compatibility at operating conditions*
- *Integral tests of fuel, structural materials*
- *Feature tests of components*
- *Fuel performance with minor actinides*
- *Cumulative ~200 dpa*
- *Long life fuel concepts ~300-500 dpa*

Target Station Can Help Fuel Cycle R&D and Advanced Reactor Technologies

- All of the advanced concepts can be tested in appropriately designed test loops
- Neutron flux tailoring can create fast or thermal spectrum test environments that match very different reactor environments at relevant temperatures
- Room for separate sodium, lead, LBE, helium, molten salt, water loops that can be used to simultaneously test materials interactions
- Candidate materials such as fuel and cladding can be irradiated in a prototypic coolant, temperature, and neutron spectrum
- Temperature is a critical parameter in materials irradiation and precise temperature control will be a key aspect of the Energy Station Test Module design
- Higher H and He generation rates for corresponding damage accumulation could allow accelerated testing of materials
- Potential test volumes in Target Station could be 100’s of liters

Target Station Capabilities

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- Flexible design allows support to multiple missions for DOE-SC-HEP, SC-NP, SC-FES, DOE-NE
- Benefits of test reactor volumes and neutron fluxes without reactor issues – licensing, fuel supply, safety, waste
- Robust technology allows it to be designed and constructed with today's technology in order to fill gaps in tomorrow's technology
- Continuous wave, high availability, high beam current provides potential for irradiation tests to high fluence
- Energy distribution of spallation neutrons similar to fast reactor fission spectrum but with high energy tail up to proton energy
- Ability to tailor neutron spectrum from fast to thermal as well as the gamma to neutron flux ratio
- H and He generation in materials higher than in reactor allowing accelerated aging testing
- Potential for beneficial isotope production and/or neutron beams simultaneous with irradiation testing

Introduction/Summary

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